Status report on the GLACIER project

André Rubbia (ETHZ)

**U.S. long Baseline neutrino Experiment
Joint BNL-FNAL Study
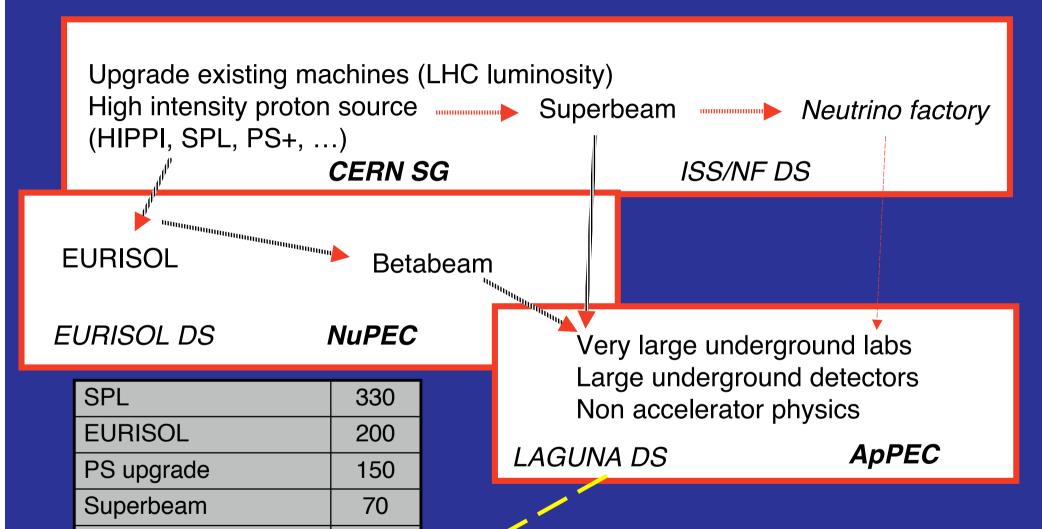Fermilab, Sep 16-17 2006**

Introduction

- The liquid Argon Time Projection Chamber (LAr TPC) is a powerful detector for uniform and high accuracy imaging of massive active volumes. It is based on the fact that in highly pure Argon, ionization tracks can be drifted over distances of the order of meters. Imaging is provided by position-segmented electrodes at the end of the drift path, continuously recording the signals induced. T_0 is provided by the prompt scintillation light.

- We have proposed a conceptual, scalable design for very large liquid Argon TPCs, with masses potentially up to order 100 kton (GLACIER).

- The feasibility and optimization of this design is the aim of an R&D program currently underway.

- According to the European ApPEC (=Astroparticle Physics European Coordination) roadmap, the design of large underground detectors should converge towards a possible "proposal" around 2010 (LAGUNA design study=Large Apparati for Grand Unified and Neutrino Astrophysics).

- The future of neutrino beams in Europe is currently coordinated by BENE and eventually most likely by the CERN Strategy Group (SG)

LAGUNA is a coordinated European effort

- At the ApPEC "Munich meeting" held on November 2005, a coordinated effort among the 3 "liquids" has been proposed and accepted. Large detectors like Water Cherenkov, Liquid Scintillator and Liquid Argon present important physics complementarities and also a lot of common R&D needs. They have to work in synergy.

- The purpose is to develop conceptual designs for European large scale liquid detectors into coherent and well-coordinated EU wide efforts towards a common physics goal and solving common problems together, taking into account the unique technological expertise in Europe and the other existing or planned programs in the world, such that mature designs and credible scenarios can be proposed around 2010.

- During the last months, an effort has been made to consolidate these ideas into a format compatible with potential EU Framework Programme FP7 instruments. The idea is to submit a common EU design study on the three liquids by beginning of 2007.

- This effort, although oriented towards a potential infrastructure in Europe, should allow Europeans to contribute in a coherent way and possibly with better impact, to the on-going discussions worldwide (e.g. NNN workshops).

Overall picture of activities (and dreams…)

Upgrade existing machines (LHC luminosity)

High intensity proton source ┈┈┈▶ Superbeam ┈┈┈▶ *Neutrino factory*
(HIPPI, SPL, PS+, …)

CERN SG   *ISS/NF DS*

EURISOL   Betabeam

EURISOL DS   **NuPEC**

Very large underground labs
Large underground detectors
Non accelerator physics

LAGUNA DS   **ApPEC**

SPL	330
EURISOL	200
PS upgrade	150
Superbeam	70
β decay ring	340
Lab + detectors	500
Total	**1500**

Rough cost in M€ (no manpower, no contingencies)

Where?

IUS

Institute of Underground Science in Boulby mine, UK

Laboratoire Souterrain de Modane, France

CENTRE FOR UNDERGROUND PHYSICS IN PYHÄSALMI MINE
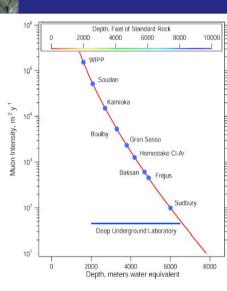
Currently there is no available sight to host very large scale detectors in Europe!

- New facilities will have to be excavated or old one extended
- What depth?
- What other synergies? (beamline distance)
- What is the distance from reactors?

Polkowice-Sieroszowice

LSC

Laboratorio Subterraneo de Canfranc, Spain

LNGS

Laboratori Nazionali del Gran Sasso, Italy

Site investigation

- Work closely with Integrated Large Infrastructure for Astroparticle Science ILIAS-N2-WG1
  - And respective WG in ILIAS-next
  - ILIAS N2: propose to organise a technical meeting on site expansions and technical issues in November 2006

- Pre-feasibility studies
  - Partially done (Fréjus, Pyhäsalmi)
  - Extend to LNGS, Sieroszowice, …
  - Green fields
  - Report on constructability: possible show-stoppers

- Feasibility studies (for all sites)
  Including thorough rock sampling, rock simulations
  - Pre-plan for construction
  - Cost estimates
  - Site pre-selection

- Final goal $\Rightarrow$ Detailed plans for site construction
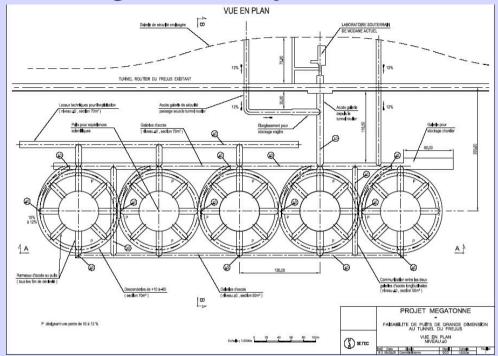
Very preliminary sites vs experiments

		Mt Water Cerenkov	50 kt Liquid Scintillator	100 kt Liquid Argon
Fréjus	Tunnel / hard rock	√√√	√√	√√
Gran Sasso	Tunnel / soft rock	√	√√	√
Canfranc	Tunnel	?	?	?
Pyhäsalmi	Mine / hard rock	√	√√√	√√
Boulby	Mine / salt (potash)	?	?	?
Polkowice - Sieroszowice	Mine / salt & rock	√	√√	√√√
Green fields	Own shaft / Hard rock	√	√	√√√
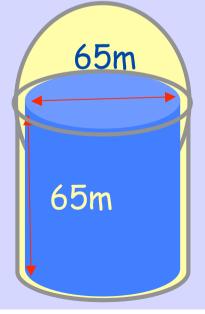
√√√ primary interest; √√ probably; √ unlikely; ? unknown

Pre-feasibility study in the central region of Fréjus tunnel

Excavation engineering pre-study has been done by SETEC & STONE companies

1) the best site (rock quality) is found in the middle of the mountain, at a depth of 4800 mwe : a really good chance !

2) of the two considered shapes : "tunnel" and "shaft", the "shaft (= well) shape" is strongly preferred

3) Cylindrical shafts are feasible up to :

a diameter Φ = 65 m and a full height h = 80 m ($\approx$ 250 000 m^3)

4) with "egg shape" or "intermediate shape" the volume of the shafts could be still increased

5) The estimated cost is $\approx$ 80 M€ X Nb of shafts

65m

65m

Scenarios:

3 shafts ≈ 450 ktons H2O

4 shafts ≈ 600 ktons H2O

+1 shaft ≈ 100 kton LAr ?
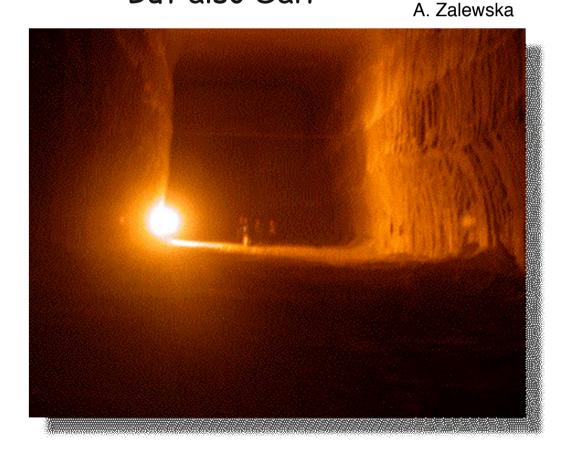
Sieroszowice mine (Poland) - big salt cavern

Copper – 6th position
in the world's exploitation
ranking
 Silver – 2nd position
But also Salt

A. Zalewska

Volume (100x15x20) m^3

Depth ~950 m from a surface
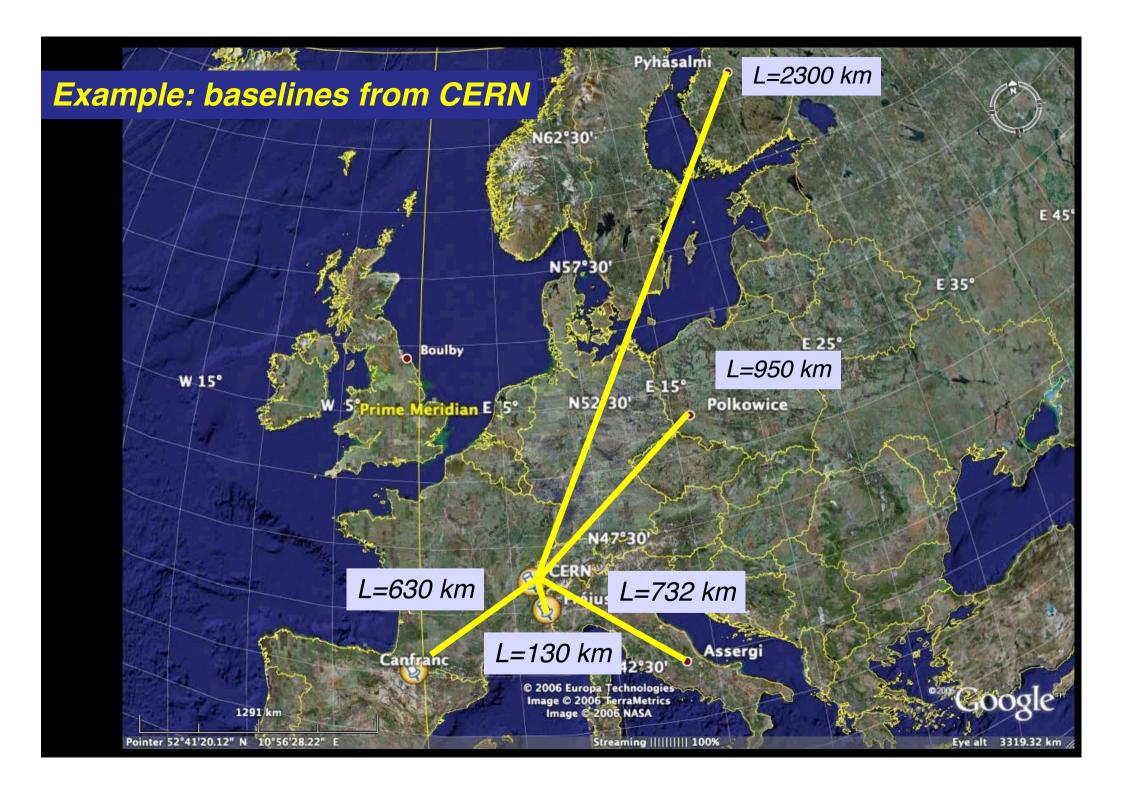
Salt layer ~70 m   thick

Temperature ~35^{0}C

Very good radioactive
background conditions

Example: baselines from CERN

L=2300 km

L=950 km

L=630 km

L=732 km

L=130 km

CNGS off-axis:

See hep-ph/0609106

LNGS

Distance from CERN

Off-axis angles

OA 0.5 deg
OA 0.75 deg
OA 1 deg
OA 1.5 deg
OA 2 deg
OA 2.5 deg

500 km
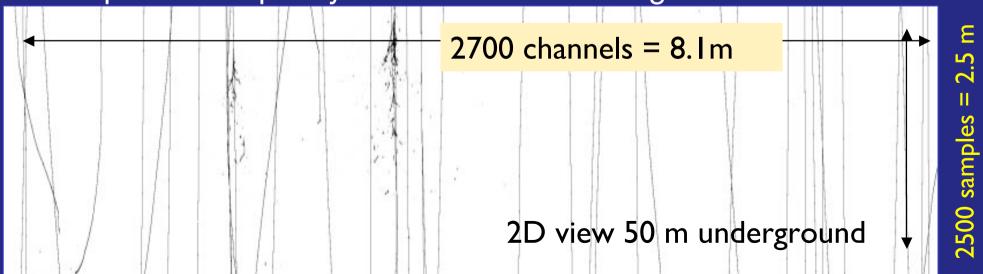600 km
700 km
800 km
900 km
1000 km
1100 km

Anywhere ? Shallow depth in green field

If rock is well known and <u>very good quality</u> in a given site, a new hole in virgin ground can be considered:
• 200 m depth relatively "easy"
• Excavation cost ≈ 5-10 M€ for shaft and ≈20M€ for 100 kton LAr experimental hall
• 1400 m possible ≈ +20 M€
(J. Peltoniemi)

Depth rock	Total crossing muons (E> 1GeV) per 10ms	Fiducial mass after slice of size D around each muon is vetoed
		D=10 cm
Surface	13000	…
50 m	100	50 kton
188 m	3.2	98 kton
1 km w.e	0.65	100 kton
2 km w.e	0.062	100 kton
3 km w.e	0.010	100 kton

Example of occupancy in LAr @ 50 m underground:

2700 channels = 8.1m

2500 samples = 2.5 m

2D view 50 m underground

Detector concept:

The Giant Liquid Argon Charge Imaging ExpeRiment (GLACIER)

GLACIER list

A. Badertscher, R. Chandrasekharan, L. Kaufmann, L. Knecht, M. Laffranchi, A. Meregaglia, M. Messina,
G. Natterer, P.Otiougova, A. Rubbia, J. Ulbricht
ETHZ (Switzerland)
A.Ereditato, M. Hess, S. Janos, U. Moser, N. Savvinov, H.U. Schuetz

Bern University (Switzerland)

A.Bueno, J. Lozano, S. Navas
Granada University (Spain)
D. Autiero, Y. Déclais, J. Marteau
IPN Lyon (France)
N. Spooner, H. Chagani, E. Daw, V. Kudryavtsev, P. Lightfoot, P. Majewski
Sheffield University (UK)
C. Beduz, Y. Yang
Cryogenic department, Southampton University (UK)
S. Gninenko
INR Moscow (Russia)
A.Zalewska
INP Krakow (Poland)
J. Kisiel
US Katowice (Poland)
E. Rondio
UPS Warszawa (Poland)
D. Kielczewska
UW Warszawa (Poland)
J. Sobczyk
UW Wroclaw (Poland)

Giant Liquid Argon Charge Imaging ExpeRiment

Electronic crates

GLACIER 100 kton

hep-ph/0402110
Venice, 2003

$\phi \approx 70\ m$

A scalable design:

10 kton

$h = 20\ m$
Max drift length

Passive perlite insulation

Single module cryo-tanker based on industrial LNG technology

Project: Large Underground Argon Storage Tank

A feasibility study mandated to Technodyne Ltd (UK): Feb-Dec 2004

Could potentially be magnetized

**New method R/O
Very long drift**

Charge readout plane

GAr

$E \approx 3\ kV/cm$

Extraction grid

E-field

LAr

$E \approx 1\ kV/cm$

Electronic racks

Field shaping electrodes

UV & Cerenkov light readout photo-detectors

The concepts for the scalable design

- **Petrochemical industrialization**
  - ➡ Proven LNG tanker with standard aspect ratio
  - ➡ Vertical electron drift for full active volume
- **Novel method of readout**
  - ➡ A new method for charge readout to allow for a very long drift path
  - ➡ To avoid use of readout wires, which can be hardly mechanically and electrically scaled (S/N) and with disfavored use in conjunction with magnetic fields (induction).
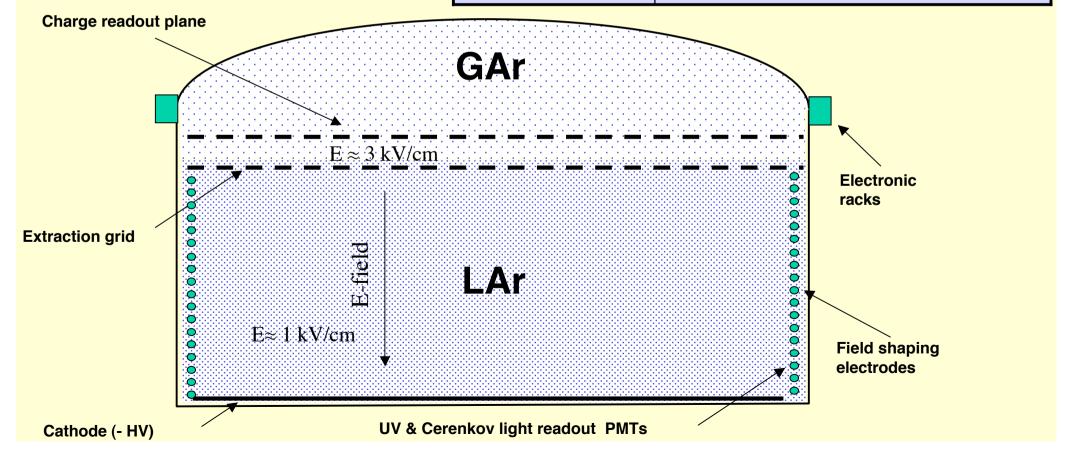 - ➡ A path towards pixelized readout for 3D images.
- **Voltage multiplier**
  - ➡ Extend drift voltage by additional of stages, w/o VHV feed-through
- **Very long drift path**
  - ➡ Minimize channels by increasing active volume with longer drift path
- **Light readout on surface of tanker**
- **Immersed superconducting solenoid for B-field**

The detector layout

Single detector: charge imaging, scintillation, possibly Cerenkov light

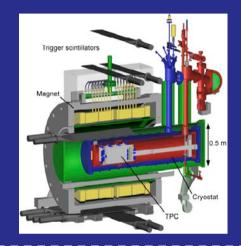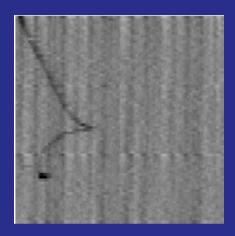| Dewar	$\phi \approx$ 70 m, height $\approx$ 20 m, perlite insulated, heat input $\approx$ 5 W/m^2
Argon storage	Boiling Argon, low pressure (<100 mbar overpressure)
Argon total volume	73000 m^3, ratio area/volume $\approx$ 15%
Argon total mass	102000 tons
Hydrostatic pressure at bottom	3 atmospheres
Inner detector dimensions	Disc $\phi \approx$70 m located in gas phase above liquid phase
Charge readout electronics	100000 channels, 100 racks on top of the dewar
Scintillation light readout	Yes (also for triggering), 1000 immersed 8" PMTs with WLS
Visible light readout	Yes (Cerenkov light), 27000 immersed 8" PMTs of 20% coverage, single γ counting capability

Charge readout plane

GAr

$E \approx 3$ kV/cm

Extraction grid

Electronic racks

LAr

E-field

$E \approx 1$ kV/cm

Field shaping electrodes

Cathode (- HV)

UV & Cerenkov light readout PMTs
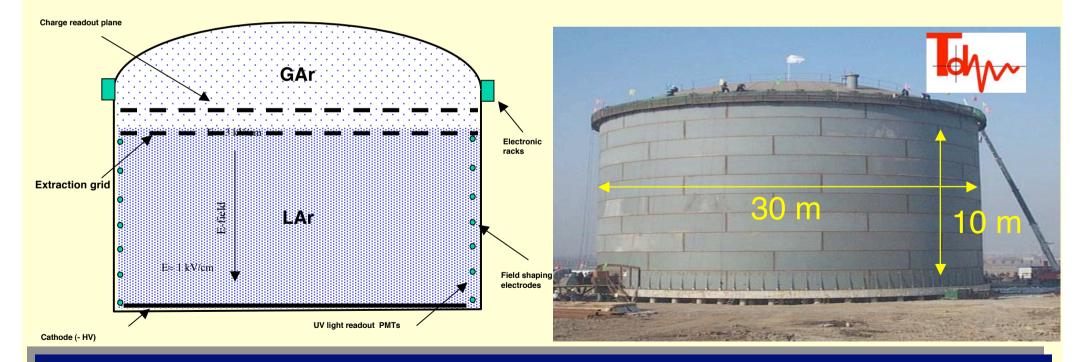
A scalable design: 10 kton prototype

- 10% full-scale prototype
- Shallow depth
- **Physics program on its own**
(e.g. sensitivity for p→νK: $\tau > 10^{34}$
yrs for 10 years running)
- Complementary to SuperK

Dewar	$\phi \approx$ **30 m, height** $\approx$**10 m**, perlite insulated, heat input $\approx$ 5 W/m²
Argon storage	Boiling Argon, low pressure (<100 mbar overpressure)
Argon total volume	7000 m³, ratio area/volume $\approx$ 33%
Argon total mass	9900 tons
Hydrostatic pressure at bottom	1.5 atmospheres
Inner detector dimensions	Disc $\phi \approx$30 m located in gas phase above liquid phase
Charge readout electronics	30000 channels, 30 racks on top of the dewar
Scintillation light readout	Yes (also for triggering), 300 immersed 8" PMTs with WLS

Charge readout plane

GAr

Electronic racks

Extraction grid

E-field

LAr

E= 1 kV/cm

Field shaping electrodes

UV light readout PMTs

Cathode (- HV)

30 m

10 m

- 1% prototype: 1 kton engineering detector, $\phi \approx$ 10m, h $\approx$ 10m, shallow depth?
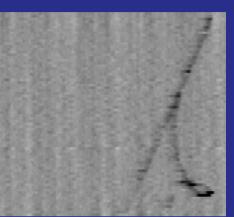
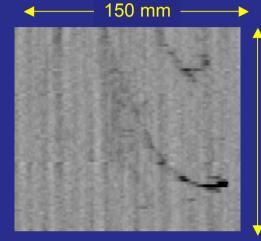# Small scale test of a 10 lt LAr TPC embedded in a B-field

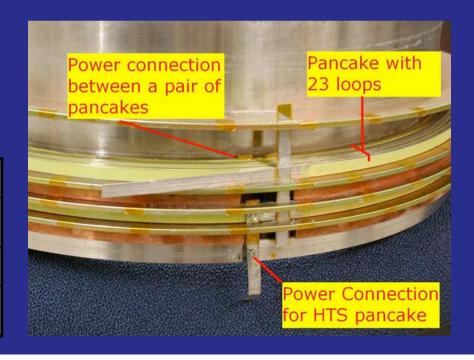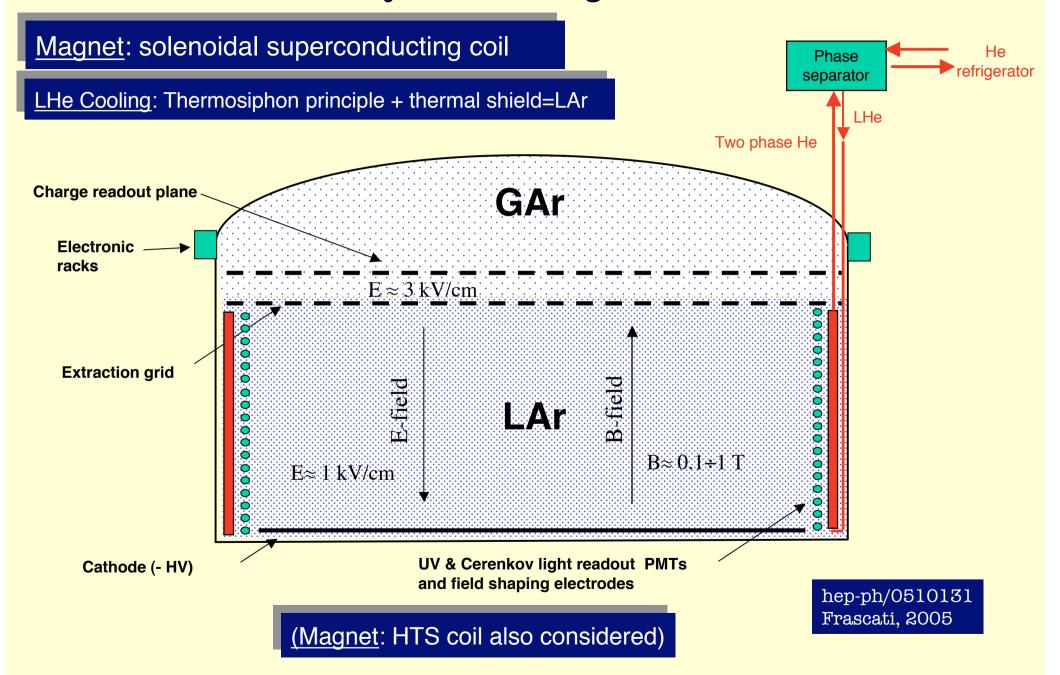## First real events in B-field (B=0.55T):

150 mm

150 mm

New test: small test solenoid built wit HTS wire
(American Superconductor)

Made of 4 pancakes, total HTS wire length: 80m

Temperature	LN$_2$ (77K)	LAr (87K)
Max. applied current	145 A	80 A
On-axis B-field	0.2 T	0.11 T
Coil resistance at 4A	6 μΩ	6 μΩ

Power connection between a pair of pancakes

Pancake with 23 loops

Power Connection for HTS pancake

Tentative layout for a magnetized detector

Magnet: solenoidal superconducting coil

LHe Cooling: Thermosiphon principle + thermal shield=LAr

Phase separator

He refrigerator

LHe

Two phase He

Charge readout plane

Electronic racks

GAr

$E \approx 3\,\text{kV/cm}$

Extraction grid

E-field

LAr

B-field

$E \approx 1\,\text{kV/cm}$

$B \approx 0.1 \div 1\,\text{T}$

Cathode (- HV)

UV & Cerenkov light readout PMTs and field shaping electrodes

hep-ph/0510131
Frascati, 2005

(**Magnet**: HTS coil also considered)

Tentative coil parameters

Other examples: ALEPH, CDF, ATLAS Toroids, AMS-II

	10 kton LAr			100 kton LAr			ATLAS solenoid	CMS
Magnetic induction (T)	0.1	0.4	1.0	0.1	0.4	1.0	2.0	4.0
Solenoid diameter (m)	30			70			2.4	6
Solenoid length (m)	10			20			5.3	12.5
Magnetic volume (m^3)	7700			77000			21	400
Stored magnetic energy (GJ)	0.03	0.5	3	0.3	5	30	0.04	2.7
Magnetomotive force (MAt)	0.8	3.2	8	1.6	6.4	16	9.3	42
Radial magnetic pressure (kPa)	4	64	400	4	64	400	1600	6500
Coil current (kA)	30 (I/I$_c$=50%)						8	20
Total length conductor (km)	2.5	10	25	12	57	117	5.6	45
Conductor type	NbTi/Cu normal superconductor, T=4.4K							
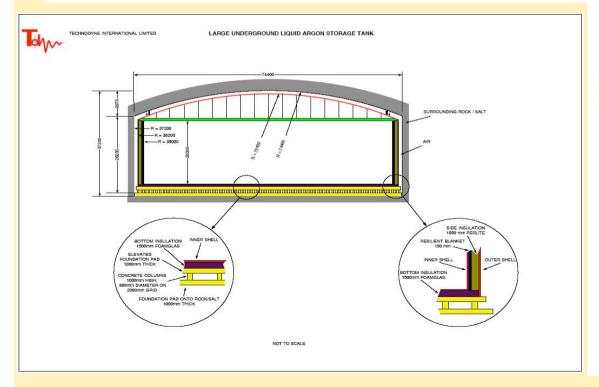
(Detailed magnetic, mechanical, thermal and quench analysis yet to be performed…)

Study of large underground storage tank

Project: Large Underground Argon Storage Tank

Document Title: Study

A feasibility study mandated to Technodyne LtD (UK): a unique opportunity!

Study duration:

February - December 2004

Tanks above surface

- Rules defined in Part 4-2 of EUROCODE 3 **(EUROCODES = The rules for design in civil engineering on a new, pan-European basis)**
- Provides principles and application rules for the structural design of vertical cylindrical <u>above ground</u> steel tanks for the storage of liquid products with the following characteristics
  - ➥ Characteristic internal pressures above the liquid level not less than -100mbar and not more than 500 mbar
  - ➥ Design metal temperature in the range of -50°C to +300°C. For tanks constructed using austenitic stainless steel, the design metal temperature may be in the range of -165°C to +300°C;
  - ➥ Maximum design liquid level not higher than the top of the cylindrical shell.
  - ➥ EN 1993-4-2 is concerned only with the requirements for resistance and stability of steel tanks. Other design requirements are covered by
    - ☛**prEN 14015 for ambient temperature tanks;**
    - ☛**prEN 14620 for cryogenic tanks;**
    - ☛**prEN 1090 for fabrication and erection considerations.**These other requirements include foundations and settlement, fabrication, erection and testing, functional performance, and details like man-holes, flanges, and filling devices.
  - ➥ Provisions concerning the special requirements of seismic design are provided in EUROCODE 8, Part 4, which complements the provisions of EUROCODE 3 specifically for this purpose. The design of a supporting structure for a tank is dealt with in EN 1993-1-1. The design of an aluminum roof structure on a steel tank is dealt with in EN 1999-1-5.

Tanks located underground

- Worldwide for LNG storage the largest above ground tank that has been built to date is the 180,000m^3 tank at Senboku Japan. The industry also perceives the requirement to increase the capacity to above 200,000m^3 in the near future. It is feasible to increase the tank capacities of Concrete / 9% Ni Steel storage tank designs to capacities above 200,000 m^3

- Underground tanks contemplated for physics experiments are relatively small compared to those used by the petro-chemical industry for above ground storage of materials.

- **Outcome of study with Technodyne**: The principles used in the design of above ground storage tanks should be readily transferable to an underground scenario.

- Extra considerations will obviously have to be taken into account when underground however, other design considerations such as wind loading and solar heating effects are eliminated from the above ground case.

Erection of a tank above surface

(1) Concrete base

(2) Concrete outer-shell

(3) Roof assembly

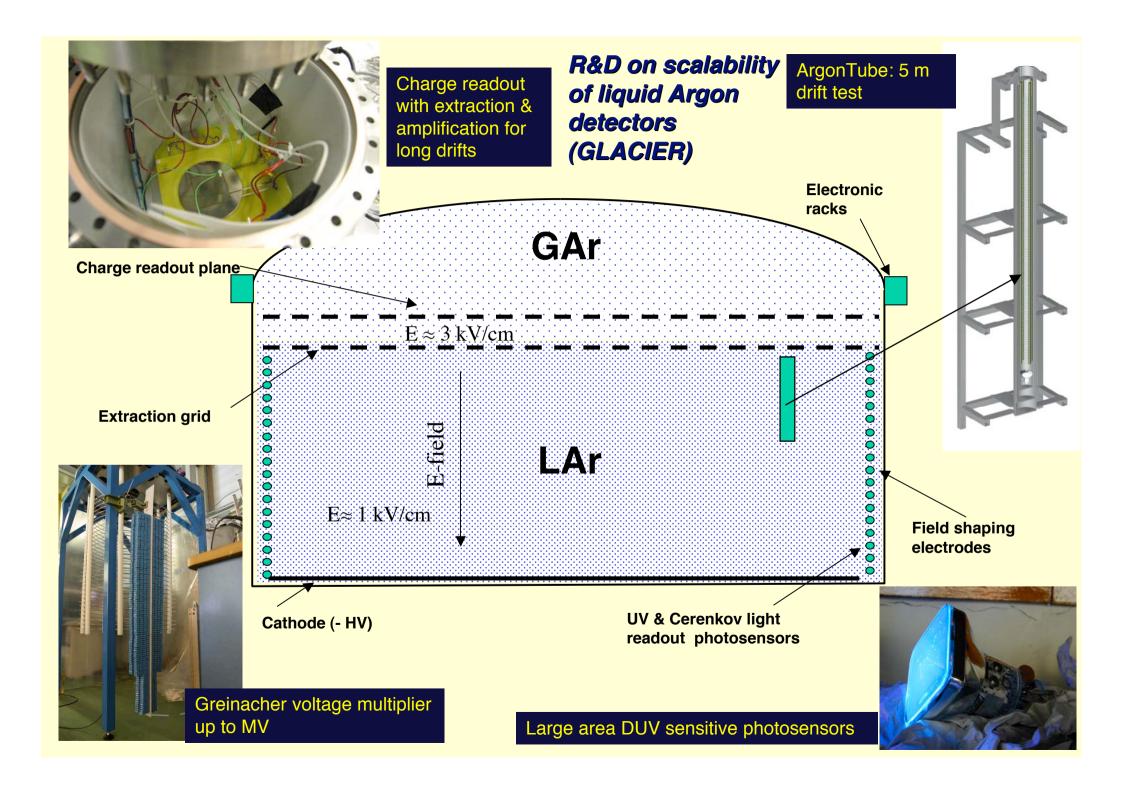**(4) Air-raising**

Tank budgetary costing

- The estimated costs tabulated below are for an inner tank of radius 35m and height 20m, an outer tank of radius 36.2m and height 22.5m. The product height is assumed to be 19m giving a product mass of 101.8 k tonnes.

Item	Description	Size	Million Euros
1	Steel	3400 tonnes	11.6
2	Insulation	16200 m^3	2.6
3	Concrete	9000 m^3	2.7
4	Electro-polishing	38000 m^2 Plate 20.5 km weld	8.2
5	Construction design / labour		18.8
6	Site equipment / infrastructure		9.8
	Total		**53.7**
6	Underground factor		2.0
	Underground tank cost		107.4
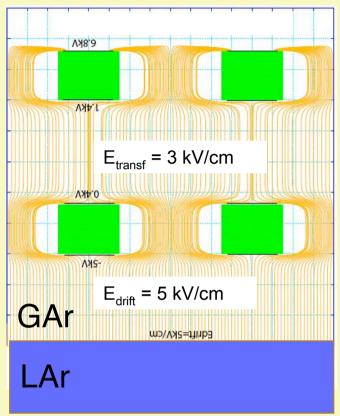
Too conservative?

More studies needed to address additional cost for underground construction

R&D

Charge readout with extraction & amplification for long drifts

R&D on scalability of liquid Argon detectors (GLACIER)

ArgonTube: 5 m drift test

Electronic racks

GAr

Charge readout plane

Extraction grid

$E \approx 3$ kV/cm

E-field

LAr

$E \approx 1$ kV/cm

Field shaping electrodes

Cathode (- HV)

UV & Cerenkov light readout photosensors

Greinacher voltage multiplier up to MV

Large area DUV sensitive photosensors

Charge readout: Thick Large Electron Multiplier (LEM)

E_{transf} = 3 kV/cm

E_{drift} = 5 kV/cm

GAr

LAr
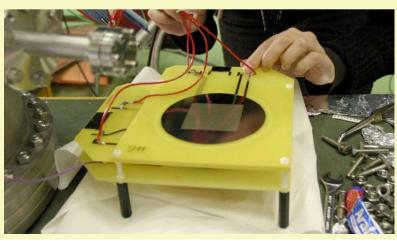
Thick-LEM: Vetronite with holes, coated with copper

→ macroscopic GEM

→ easier to operate at cryogenic temperatures

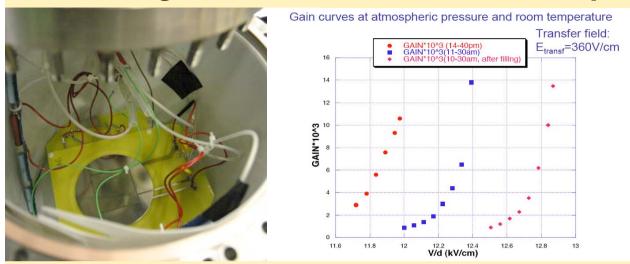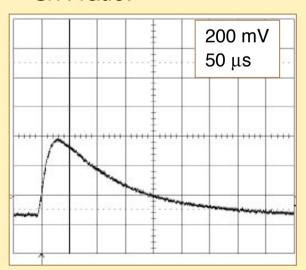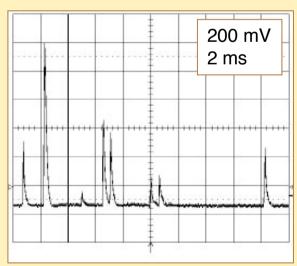→ hole dimensions: 500 μm diameter, 800 μm distance

Simulation of avalanche

•Thickness: 1.5 mm
•Amplification hole diameter = 500 μm
•Distance between centers of neighboring holes = 800 μm

→ Distance between stages: 3 mm

→ Avalanche spreads into several holes at second stage

→ Higher gain reached as with one stage, with good stability
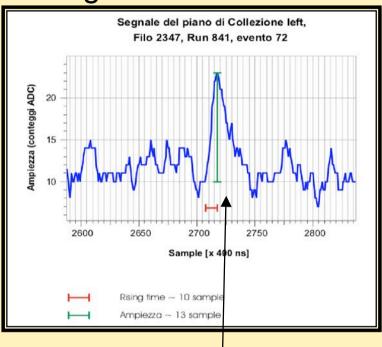
Two-stage LEM: measurements and prospects

Gain curves at atmospheric pressure and room temperature

Transfer field: E_{transf}=360V/cm

- GAIN*10^3 (14-40pm)
- GAIN*10^3(11-30am)
- GAIN*10^3(10-30am, after filling)

MIP signal in ICARUS T300

Segnale del piano di Collezione left,
Filo 2347, Run 841, evento 72

Rising time ~ 10 sample
Ampiezza ~ 13 sample

Shapes from Fe^{55} radioactive source (5.8 keV, event rate about 1kHz) of the signals from double-stage LEM system have a very clean S/N ratio.
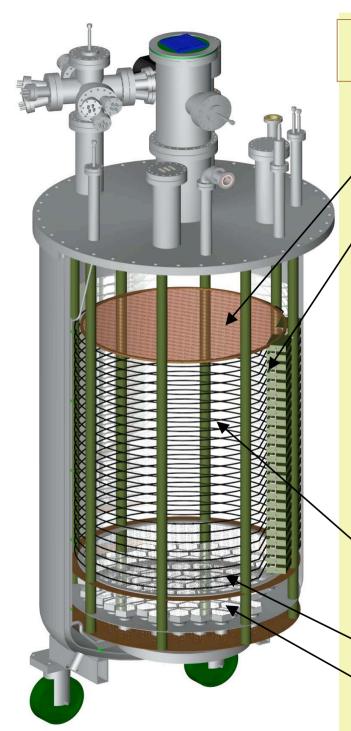

200 mV
50 μs

200 mV
2 ms

This technique solves the non-scalability of the traditional wire readout used in ICARUS
E.g. MIP signal @ ≈2 MeV/cm has poor S/N !

Full imaging TPC with LEM to be tested in 1 ton prototype @ CERN

Prototype layout: ArDM experiment

CIEMAT - ETHZ - Granada - Sheffield - Warszawa – U. Zurich

Two-stage LEM for electron multiplication and readout

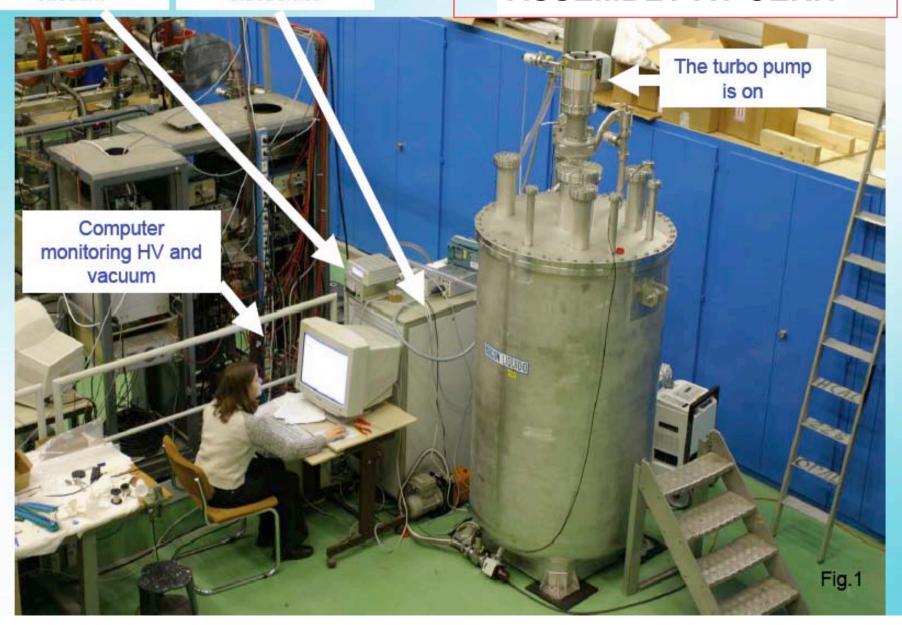Greinacher chain: supplies the right voltages to the field shaper rings and the cathode up to 500 kV

Field shapers are needed to provide a homogeneous electric field, but are thin enough to permit the scintillation light to be reflected from the container walls
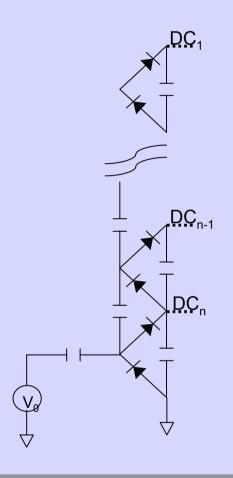
Transparent cathode

PMTs below the cathode to detect the scintillation light

Slow control for the vacuum
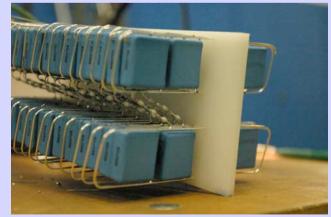
Rack for the HV electronics

ASSEMBLY AT CERN

The turbo pump is on

Computer monitoring HV and vacuum
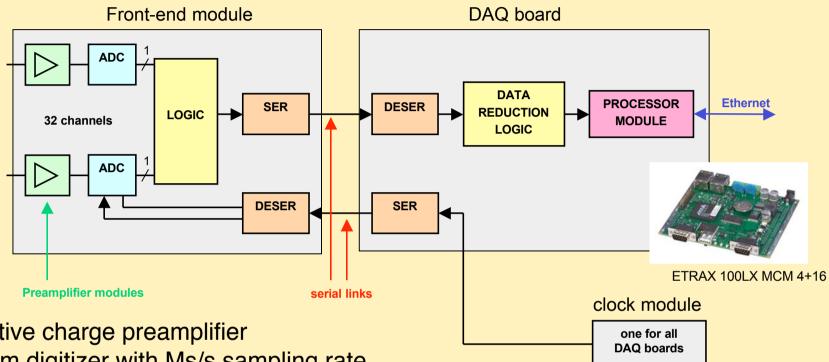
Fig.1

Drift very high voltage: Greinacher circuit

- No load to avoid resistive ripple
- Low frequency (50-500 Hz) to induce noise with a spectrum far from the bandwidth of the preamplifiers used to read out the wires or strips
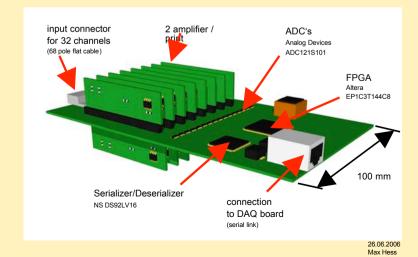- Possibility to stop feeding circuit during an event trigger

DC_1

DC_{n-1}

DC_n

V_0

Greinacher or Cockroft/Walton voltage multiplier

Up to 500 kV
≈ 4 kV/cm

Large number of channels waveform digitizers

Front-end module

DAQ board

- ADC — 1
- LOGIC
- SER
- 32 channels
- ADC — 1
- DESER
- SER

- DESER
- DATA REDUCTION LOGIC
- PROCESSOR MODULE → Ethernet

Preamplifier modules

serial links

ETRAX 100LX MCM 4+16
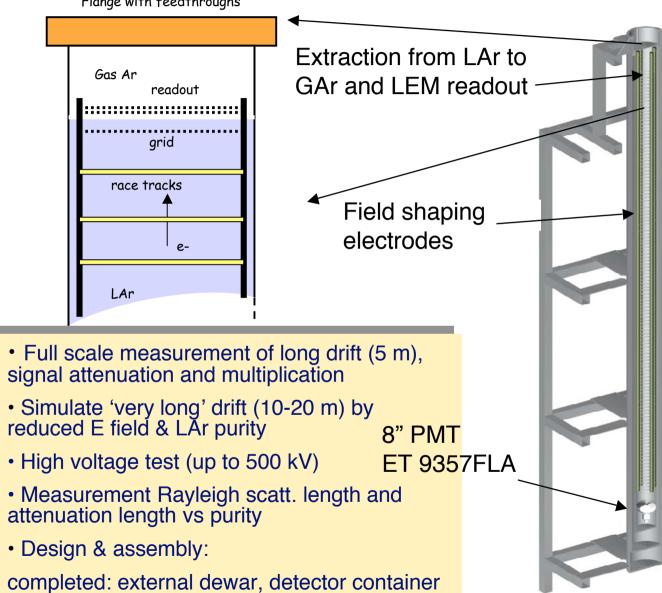
clock module

one for all DAQ boards

- fC-sensitive charge preamplifier
- Waveform digitizer with Ms/s sampling rate
- Zero suppression
- No dead-time
- Embedded processor for high level data compression and network connection
- Many channels / unit
- Affordable (<50€/channel)

input connector for 32 channels
(68 pole flat cable)

2 amplifier / print

ADC's
Analog Devices
ADC121S101

FPGA
Altera
EP1C3T144C8

100 mm

Serializer/Deserializer
NS DS92LV16

connection to DAQ board
(serial link)

26.06.2006
Max Hess

Long drift, extraction, amplification: "ARGONTUBE"

Flange with feedthroughs

Gas Ar
readout
grid
race tracks
e-
LAr

Extraction from LAr to GAr and LEM readout

Field shaping electrodes

5 meters

8" PMT
ET 9357FLA

- Full scale measurement of long drift (5 m), signal attenuation and multiplication

- Simulate 'very long' drift (10-20 m) by reduced E field & LAr purity

- High voltage test (up to 500 kV)

- Measurement Rayleigh scatt. length and attenuation length vs purity

- Design & assembly:

completed: external dewar, detector container
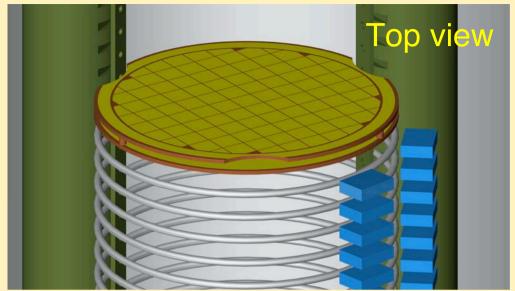
in progress: inner detector, readout system, …

Inner detector design

Top view
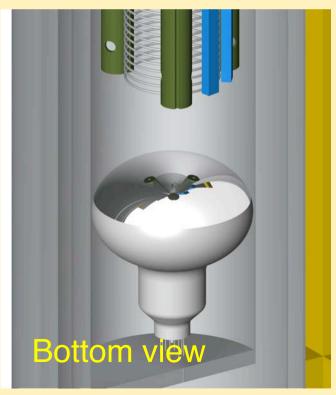
Light pulse source
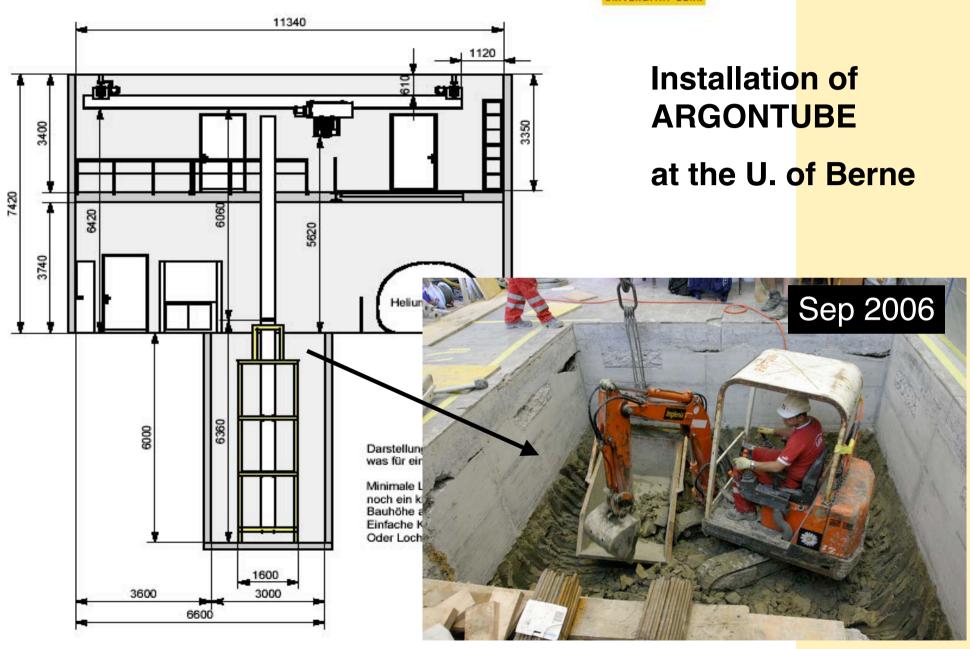
LEM

Field shaping rings
(10mm spaced)

Greinacher chain

Bottom view

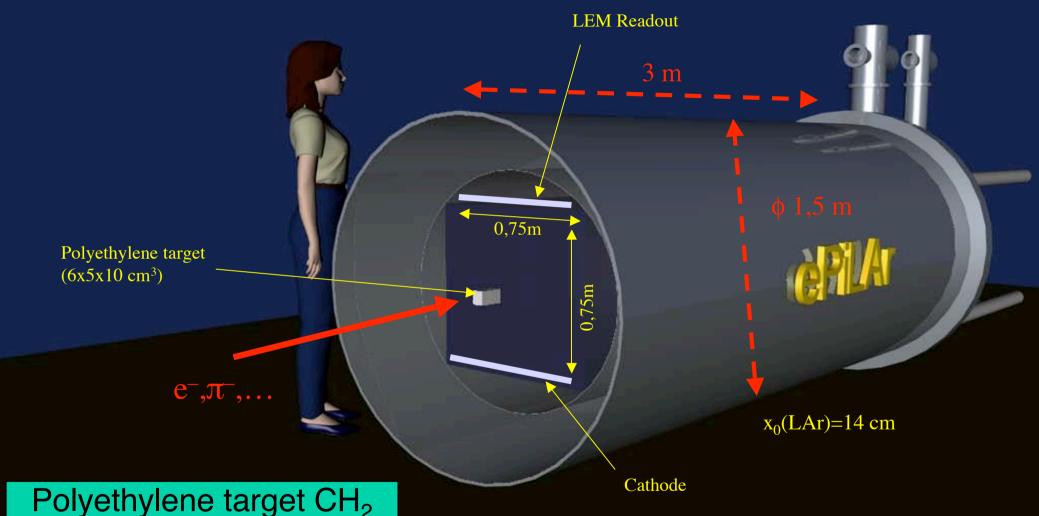**Installation of ARGONTUBE**

at the U. of Berne

Sep 2006

Further tests ?

- The liquid Argon TPC imaging offers optimal conditions to reconstruct with very high efficiency the electron appearance signal in the energy region of interest in the GeV range, while considerably suppressing the NC background consisting of misidentified π^0. MC studies show that an efficiency above 90% for signal can be achieved while suppressing NC background to the permil level. This MC result was shown to be true over a wide range of neutrino energy, typ. between 0 and 5 GeV.

- If verified experimentally, this implies that the intrinsic ν_e background will be the dominant background in superbeams coupled to liquid Argon TPCs. For this purpose, a test-beam dedicated to the reconstruction and separation of electrons from neutral pions has been discussed.
  A dedicated test beam with clean electron and pion samples would provide an important milestone, before similar analysis are performed in the more complicated neutrino beam environment.

- A 100 ton liquid Argon TPC to complement the 1 kton Water Cerenkov detector at the potential 2km site 2.5^o off-axis from the T2K beam has also been proposed. This unique experimental setup will allow to compare the performance of the liquid Argon TPC to the Water Cerenkov ring imaging and to reconstruct neutrino events directly in the same beam.
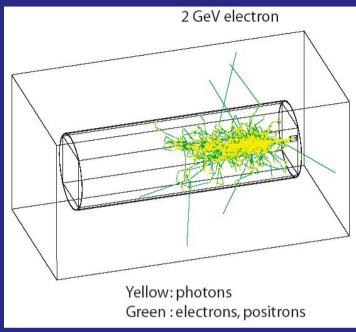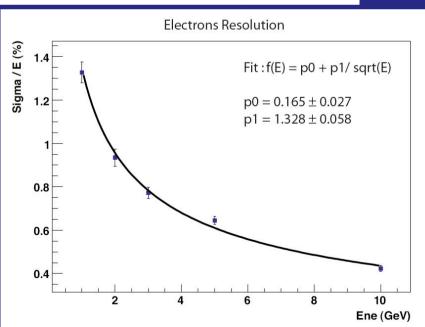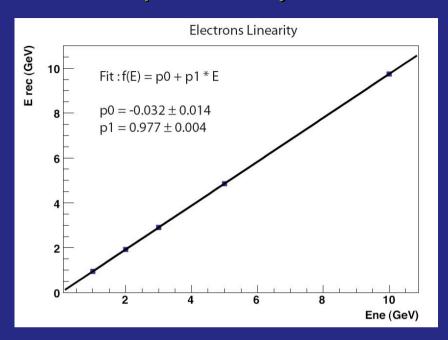
Electron and π⁰ samples:

LEM Readout

3 m

ϕ 1,5 m

0,75m

0,75m

Polyethylene target
(6x5x10 cm³)

$x_0(LAr)=14$ cm

Cathode

$e^-, \pi^-, \dots$

Polyethylene target CH_2

$\pi^- + p \rightarrow \pi^0 + n$

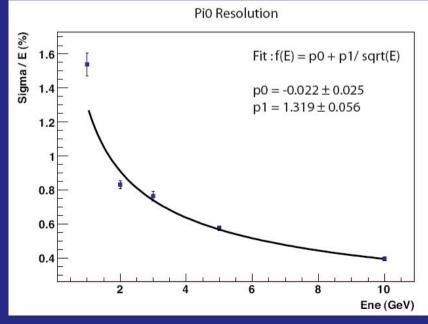$\sigma_{CH2} \approx 30 \times \sigma_{Ar} \approx 10^{-3} \sigma_{inel, CH2}$

Drift time @ 1 kV/cm ≈ 375 μs
Max rate/350 ms≈ 1000 particles

Expected shower containment (GEANT4)

2 GeV electron

Yellow: photons
Green : electrons, positrons

Electrons Linearity

Fit : f(E) = p0 + p1 * E

p0 = -0.032 ± 0.014
p1 = 0.977 ± 0.004

Electrons Resolution

Fit : f(E) = p0 + p1/ sqrt(E)

p0 = 0.165 ± 0.027
p1 = 1.328 ± 0.058

Pi0 Resolution

Fit : f(E) = p0 + p1/ sqrt(E)

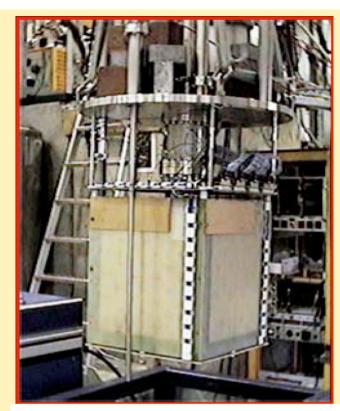p0 = -0.022 ± 0.025
p1 = 1.319 ± 0.056

Outlook

- Around 2011-2012 after a few years of running of LHC and T2K&NovA, there will be a new landscape concerning supersymmetry, unification, and hopefully the last unknown neutrino mixing angle θ_{13}.

- These will also be the times of world distribution of new very large infrastructures.

- We continue with our R&D program, necessary to extrapolate liquid Argon TPC concept to O(100 kton) detectors. The state of the art of our conceptual design and the related R&D tests and potential test beam campaigns have been presented.

- In Europe a common design study for FP7 will help reach the required critical mass needed to study the large underground detectors with the required level of details. Worldwide coordination (e.g. NNN, NUFACT workshops) will benefit from a better coordinated EU effort.

- The large underground detector physics program concerns both non-accelerator/astroparticle physics and neutrino accelerator physics. THIS IS A GREAT ASSET and it should be taken properly into account.

50 lt chamber at CERN WANF beam (1997)

Top View

last CHORUS
scintillator plane

VN

Vt

C1

C2

T1   T2

50L TPC

Beam

A
B

veto counter

Pb converter

shower
counter

trigger
counter

NOMAD

NOMAD
trigger counters

NOMAD veto